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PLASMA SIMULATION OF ION ACCELERATION BY LOWER HYBRID WAVES IN THE SUPRAURORAL REGION

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Abstract. The generation of lower hybrid waves below field-aligned potential drops and the effect of the resulting turbulence on the ion population in the supraroral region are studied using particle plasma simulations. To describe the ion acceleration observed in the simulation, a theoretical model is developed using mode-mode coupling processes to generate the low-phase-velocity VLF waves with which the ions first interact. By scaling the simulation results, we show that interaction between the ions and the lower hybrid waves can account for the acceleration necessary to produce supraroral energetic ion conic events.

Introduction

It is becoming more widely accepted that the energetic ion conics [Mizera et al., 1981] observed below field-aligned potential drops in the supraroral region are produced as the result of ion acceleration by the VLF turbulence observed there [Mozer et al. 1980]. The turbulence is generated through the instability of the auroral electron distribution accelerated parallel to the geomagnetic field by the parallel electric field [Maggs and Lotko, 1981]. A model for the formation of ion conics in this way was proposed by Chang and Coppi [1981]. Acceleration nearly perpendicular to the field line by VLF turbulence near the lower hybrid frequency is followed by the adiabatic folding of velocities as the ions mirror and travel up the geomagnetic field line, creating the conic velocity distribution. Detailed calculations of conics using a Monte Carlo technique to model the wave-particle interaction were carried out by Retterer et al. [1983], while Crew and Chang [1985, see also this conference] have pursued analytical calculations.

Considerable uncertainty remains in the model, however, because of the difficulty in estimating the rate of the wave-particle interaction process. Empirical estimates of the velocity diffusion tensor based on observed wave amplitudes suffer because the lack of wavenumber measurements prevents us from determining the phase velocities of the waves. We cannot rely on linear calculations to give us the wave spectrum either, because there appears to be a real difficulty in linearly exciting waves of small enough phase velocity so that the resonant portion of the ambient ion distribution can account for the observed number of particles in the conics. In addition, the self-consistent evolution of the wave spectrum has been ignored in previous work.

Plasma Simulation

To address these problems, a plasma simulation was performed [Retterer et al., 1986] to provide an independent, self-consistent means of studying the generation of the turbulence and the resulting ion acceleration. The supraroral situation was modeled by allowing a weak ($n_b/n_o \lesssim 10^{-2}$), energetic ($E_b = 1$ keV), warm ($T_b = 125$ eV) electron beam traveling along the magnetic field to destabilize a cool electron-ion plasma ($T_e = T_i = 2$ eV). We set the direction of propagation of the waves to be nearly perpendicular to the magnetic field, with $\cos^2\theta_B = m_e/m_i$ to reflect the commonly observed wave spectral peak near 1.5 times the lower hybrid resonance frequency. The velocity of the 1 keV electron beam projected onto the propagation direction is then about 32 times the initial ion thermal velocity. The phase velocities of waves excited by this beam will be far out on the tail of the ion velocity distribution, where few ions can resonantly interact with them.

Nevertheless, a finite fraction of the ions are significantly accelerated in the course of the simulation. We found that tails of energetic ions formed, emerging from both sides of the initial velocity distribution at about three times the ion thermal velocity; some ions are accelerated to velocities comparable to those of
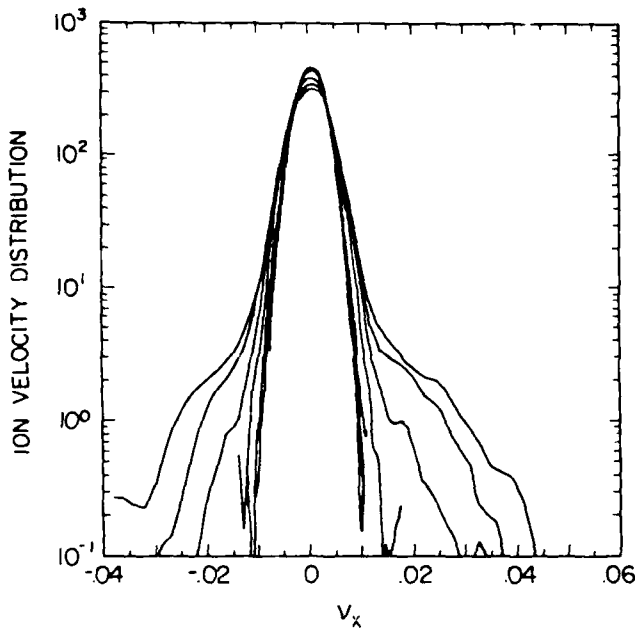
Fig. 1. The ion velocity distribution. Each
curve is a plot of the ion velocity distribution
at a fixed time. The times run from zero to
$400/\omega_{LH}$ in increments of $40/\omega_{LH}$; the velocities
are in arbitrary units in which the beam velo-
city is 0.08333.

the action of mode coupling processes. The
result is an approximately steady-state
spectrum, achieved at t≳400, which at smaller k
takes the Rayleigh-Jeans form, $|E(k,t)|^2 =$
constant.

Interpretation

The interpretation of these results is clear,
following from the extensive work devoted to the
high-frequency analogue of the problem:
electron tail formation in strong Langmuir tur-
bulence [Kruer, 1976; Goldman, 1984; and
references therein]. The intense VLF waves
linearly excited by the beam parametrically
decay into lower phase velocity VLF waves by
coupling through nonresonant quasi-modes which
are driven to finite amplitude in the turbulent
state. These lower phase velocity VLF waves are
then Landau damped by the plasma, accelerating
the ions perpendicular to the magnetic field and
the electrons (because of their restricted per-
pendicular mobility) parallel to the field.
Several calculations support this interpreta-
tion of our simulation. First, an analysis of
the nonlinear dispersion relation [Porkolab,
1977] for the coupling of two lower hybrid waves
through nonresonant quasimodes was performed.
Using the amplitude and other parameters of one
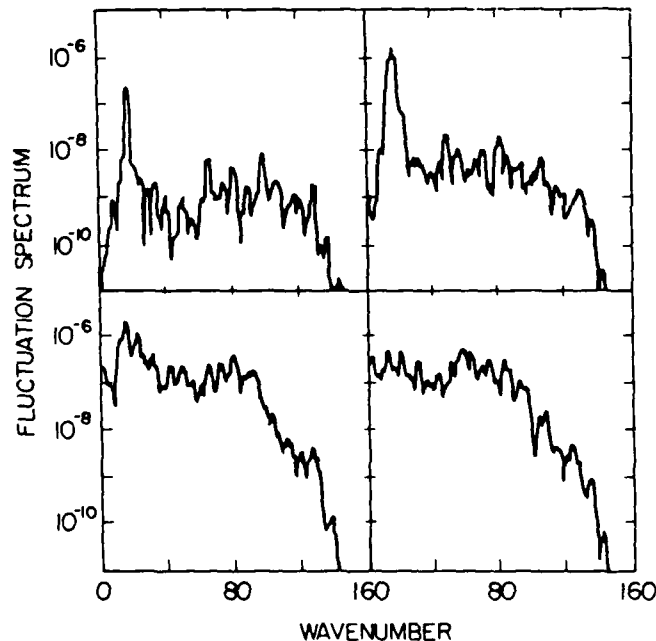of the linearly excited waves in our simulation

the electron beam. This is illustrated in
Figure 1, which presents a series of overlaid
snapshots of the ion velocity distribution at
different times. In addition to the tails, the
core of the velocity distribution showed evi-
dence of nonresonant heating. It can be fitted
by a Maxwellian velocity distribution, in which
changes in the fitted thermal velocity reflect
the changes in the total wave energy. But the
tails account for most of the energy transferred
to the ions in the course of the instability;
following wave saturation, they already contain
4% of the ions and account for half of the ion
energy. In addition, electron acceleration
parallel to the magnetic field (in both direc-
tions) is also observed, with the electrons
reaching energies comparable to those of the
ions. These accelerated electrons correspond to
the Type 1 counterstreaming electrons, observed
by DE-1 [Lin et al., 1982] in conjunction with
ion conics.

The evolution of the fluctuation spectrum is
illustrated in Figure 2. In this Figure we have
plotted $|E(\kappa,t)|^2$ as a function of k at four
times, t, where E(k,t) is the spatial transform
of the electric field. At early times (t≲240),
we see the linearly unstable modes (centered at
k=16) emerging from the background noise. From
this concentration in a relatively small region
of k space, we subsequently see the wave energy
redistribute itself throughout k space, through

Fig. 2. The wave spectrum. In each panel is
plotted $|E(k,t)|^2$ vs wavenumber k at a fixed
time. In the upper row, the times are 160 and
240; in the lower row, 320 and 400. The wave-
numbers are expressed in multiples of the fun-
damental wavenumber of the length of plasma
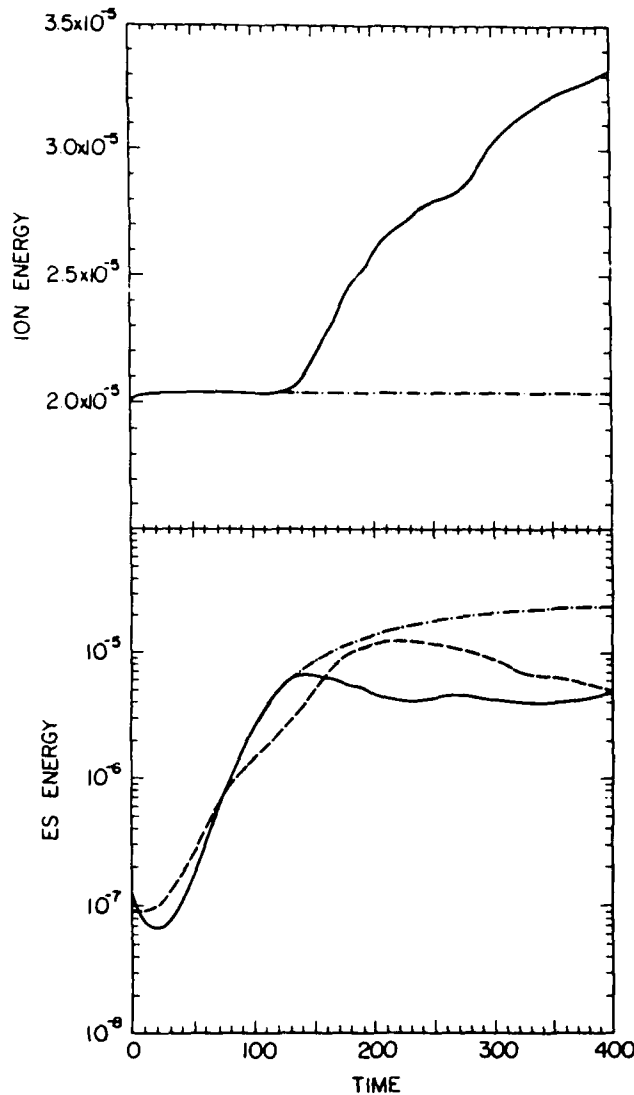included in the simulation.

Fig. 3. The energetics of the theoretical
model. The top panel gives the ion kinetic
energy (in units in which the beam energy is
2.9×10^{-4}) as a function of time; the solid
line gives the ion energy when mode coupling is
included in the model, the dot-dash line the
result without mode coupling. The bottom panel
gives the electrostatic energy of the waves with
the same coding of the lines as the top panel,
with the addition of the dashed line showing the
result from the particle simulation.

of kinetic equations, beginning with the quasi-
linear equations and adding mode coupling terms
to describe the nonlinear processes [Retterer et
al., 1986]. Numerical solution of these
equations produces an ion velocity distribution
with high energy tails and a wave spectrum simi-
lar to the ones observed in the simulation.
Figure 3 illustrates the energy budget of the
resulting calculation, with the top panel giving
the ion energy as a function of time and the
lower panel the electrostatic energy of the
waves. The units of energy are such that the
initial beam energy density is 2.9×10^{-4}. We
experimented with the model by removing the
mode-coupling terms from one run to judge its
effect on the evolution. The dot-dash lines are
the results without the mode-coupling term; all
the energy released by the beam instability
remains concentrated at long wavelengths and
little is shared with the ions. In contrast,
with mode-coupling active most of the energy
liberated is transferred to the ions, leaving
much less in the waves, in agreement with the
results of the particle simulation, presented
here as the dashed line. In form, we see at
initial times the exponential growth associated
with the linear phase of the instability. Once
the threshold for mode-mode coupling has been
exceeded, a turbulent steady state in the waves
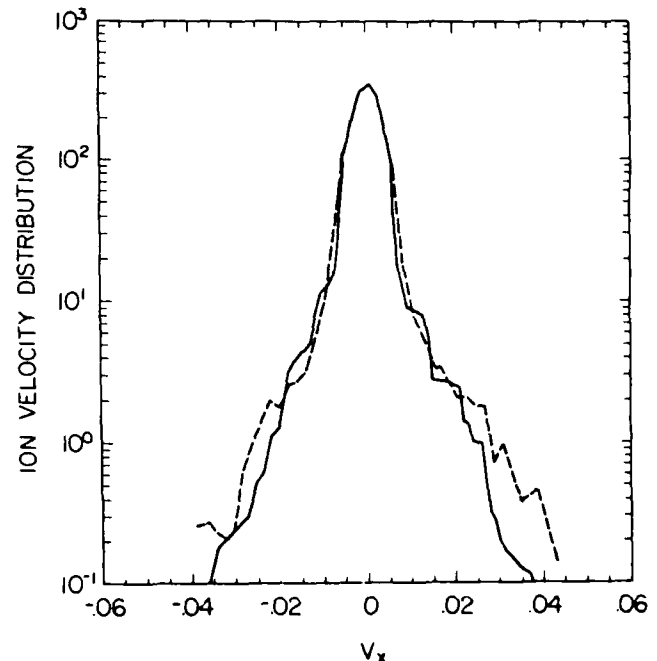is soon reached, while energy continues to be

Fig. 4. The ion velocity distribution in the
theoretical model. The solid line is a snapshot
of the ion velocity distribution at $\omega_{LH}t = 400$.
The dashed line gives the ion velocity distribu-
tion from the comparable time in the particle
simulation.

as a pump wave, we calculated the phase veloci-
ties of the sideband waves excited by the three-
wave coupling process. We found that these
velocities agreed well with the velocities at
the points where the tails emerge from the
background distribution, supporting the argument
that Landau damping of these sidebands accelera-
tes the ions. We then formulated a simple set

transferred through the waves from the beam to the ions. In the solution without mode coupling, on the other hand, the wave energy continues to grow, although the growth rate slows as the beam velocity distribution forms a plateau at the phase velocities of the fastest-growing modes. Without mode coupling, the energy transferred to the ions is negligible.

The detailed ion velocity distribution in the mode coupling calculation shows the high-velocity tails characteristic of the particle simulation. Figure 4 shows a snapshot of the ion velocity distribution at $\omega_{LH}t=400$, illustrating the acceleration of the tails. The dashed curve here gives the comparable ion velocity distribution from the particle simulation.

We conclude from these comparisons that our theoretical model with mode-coupling does satisfactorily describe the phenomena observed in the particle simulations. While the simple resonant-quasilinear-diffusion model is adequate to describe the effect of the turbulence on the particles, a full nonlinear treatment is necessary to describe the evolution of the turbulence.

Conclusion

Scaling of our simulation results to suprauroral conditions gives results which agree well with data from observed ion conics; fraction of accelerated ions $\sim 10^{-3}$ to 10^{-2}; average energy ~ 50 eV; maximum energy ~ 1 keV. The one-dimensional model presented here does overestimate the wave electric field, predicting values of the order of 100 mV/m for the total spectrum. It does agree with the observations in demonstrating that an overwhelming portion of the energy removed from the beam goes into particle acceleration rather than waves, the proportion here being roughly ten to one. The simulation and analysis of the phenomena of lower hybrid acceleration in two or three dimensions must be postponed to a later report. As a preliminary, we note that an analysis of lower-hybrid parametric decay under suprauroral conditions has been performed by Koskinen [1985, see also this conference]. He reports that decay through nonresonant quasimodes is the dominant process and that the threshold of wave amplitude may be one mV/m or smaller, insuring

that the mode-coupling processes which we have discussed can operate in the suprauroral region.

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